NSTX-U *Supported by* U.S. DEPARTMENT OF ENERGY | Office of Science

Development of Bolometry Diagnostics for NSTX-U

M.L. Reinke (ORNL)

and the NSTX Research Team

NSTX-U Physics Meeting
PPPL
8/10/15

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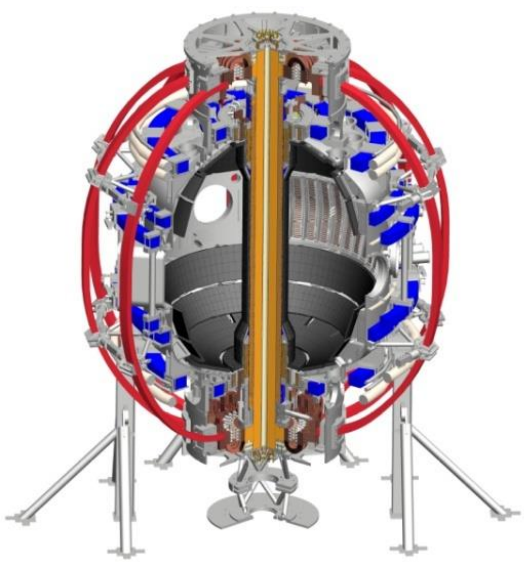

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Motivation

- knowing power loss from radiation an important measurement to support tokamak operations and physics
- NSTX was under-diagnosed in this area, and presently configured NSTX-U is as well

Tokamak	Resistive Bolometers	AXUV Diodes
NSTX-U	**0**	**80**
C-Mod (FY15)	28	64
C-Mod (FY11)	32	172 + (80 Ly_{α})
ASDEX-U	112	256
MAST-U	64	0
JET	76	0
TCV	64	140
DIII-D	48	20

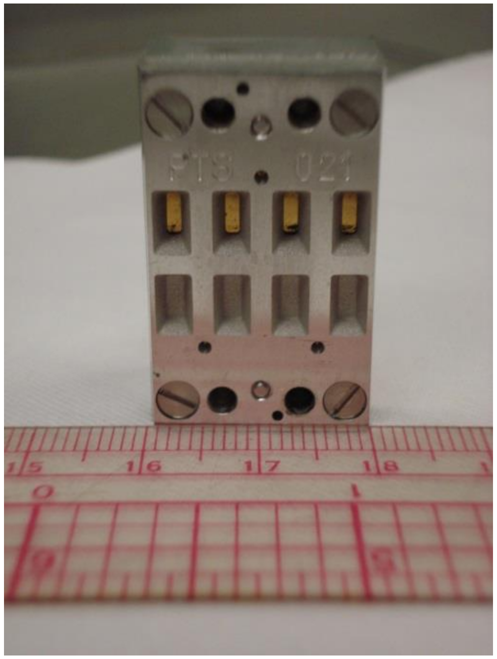
- at high heating power, NSTX-U heat flux mitigation critical
  - radiative exhaust a robust tool, widely used
- without diagnostic upgrades we will lack
  - data for physics studies
  - an ability to communicate research w/ other devices

Overview

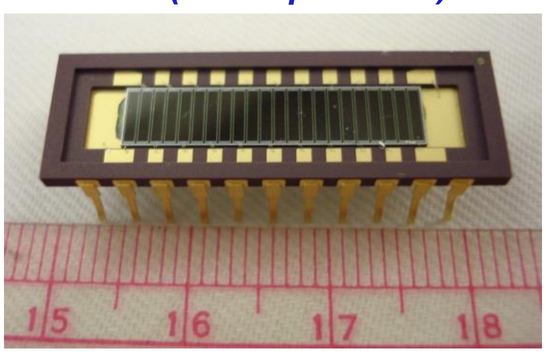
- different radiation measurement techniques
  - discuss AXUV diodes and resistive bolometers
  - **demonstrate AXUV diodes are insufficient for power balance**
- radiation measurement desires from the NSTX-U team and feasibility
- NSTX resistive bolometer and plans for NSTX-U divertor resistive bolometers for FY17
  - viewing geometry of J-UPPER and I-LOWER pinhole cameras
  - signal estimates; crude and using SOLPS
  - survivability of sensors
- considerations for longer term development of core and global radiation measurements

What is Meant By the Term ‘Bolometer’?

4-channel resistive bolometer from IPT-Albrecht



20-channel AXUV diode from IRD (now Optodiode)

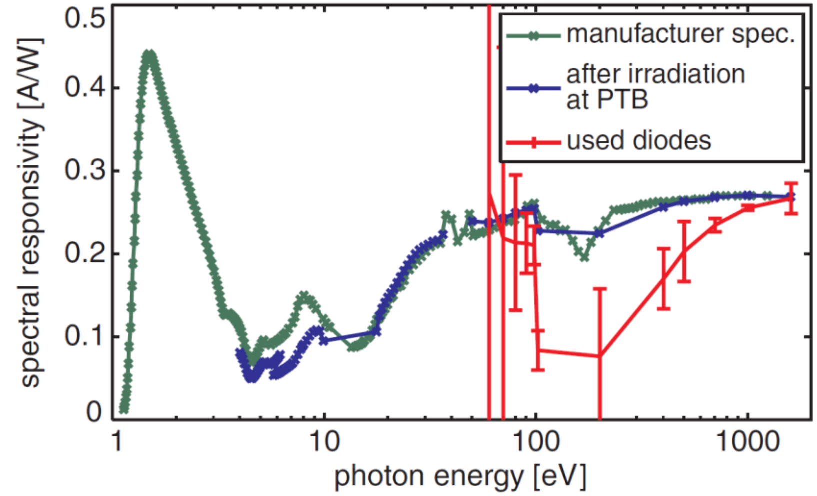


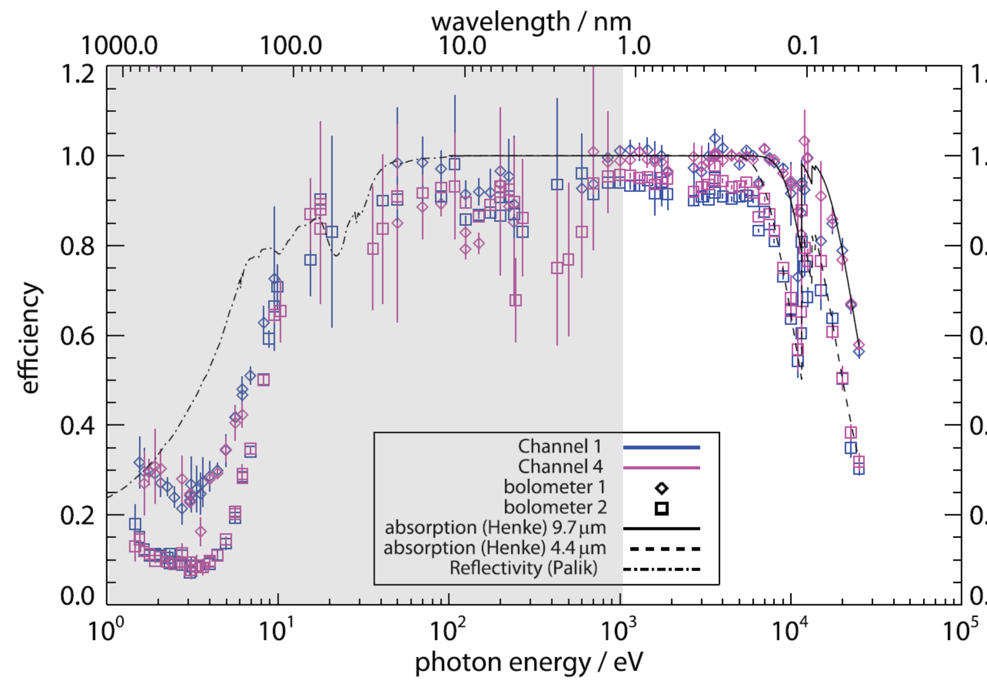
- literal: measurement of something thrown, bolo
- practical definition is the measurement of incident radiation through a rise in temperature
  - ‘resistive’ bolometer via resistance change
    - measured via AC-excited Wheatstone bridge
  - ‘IR’ bolometer via IR emission
  - both use ‘foils’ to absorb radiation
- Absolute eXtreme UltraViolet (AXUV) diodes are Si sensors that generate photocurrent from incident radiation – a ‘brand name’ diode
  - designed to be sensitive to low energy photons
- expectation both in and out of fusion is to NOT use ‘bolometer’ when referring to AXUV diodes
  - need to change PPPL vocabulary to avoid confusion inside and outside the group

AXUV Diodes and Bolometers Have Different Sensitivity

- neither AXUV diodes nor bolometers are perfect
  - foils reflect light in visible, but generally low power loss
  - foils absorb neutral power loss

*M. Bernert, RSI **85** 033503 (2014)*



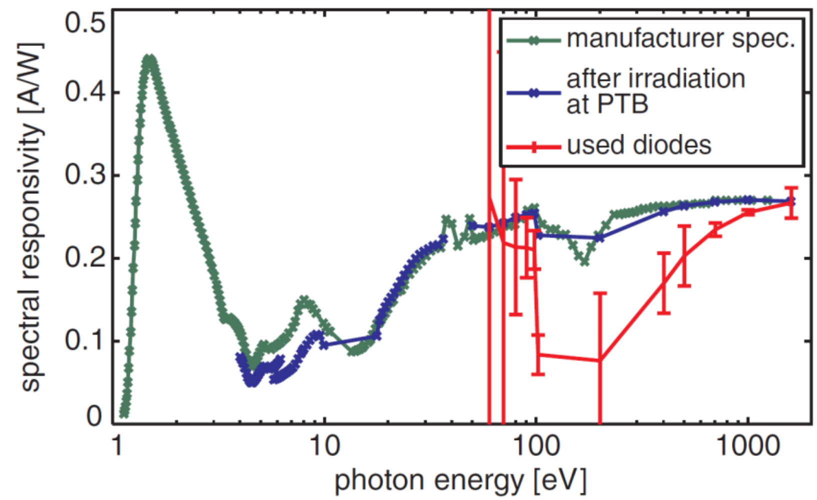


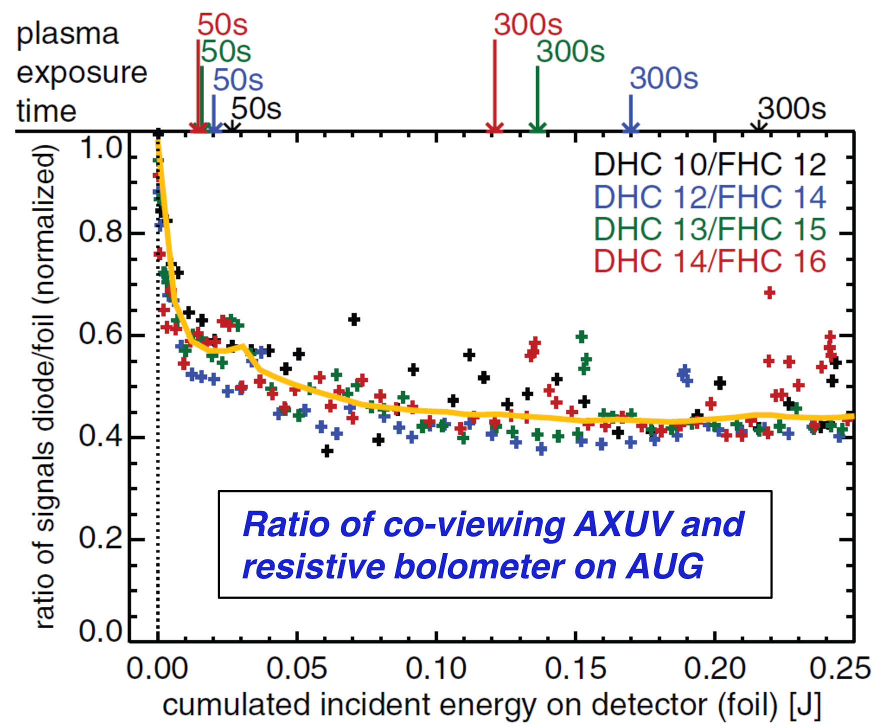
*H. Meister, RSI, **84** 123501 (2013)*

AXUV Diodes and Bolometers Have Different Sensitivity

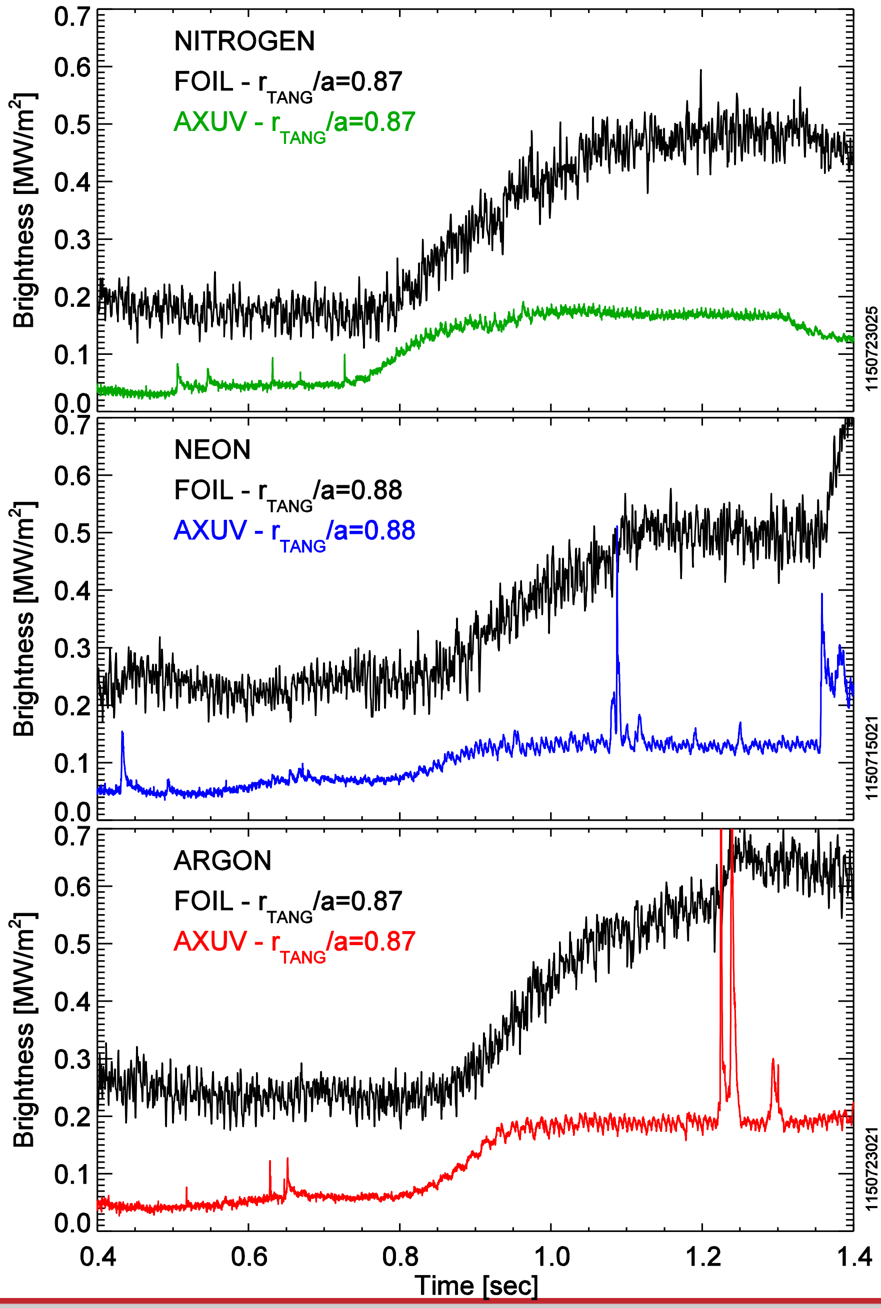
- neither AXUV diodes nor bolometers are perfect
  - foils reflect light in visible, but generally low power loss
  - foils absorb neutral power loss
- AXUV diodes have been demonstrated to be damaged during operations (VUV, neuts?)
  - stabilizes after a certain ‘burn-in’
    - C-Mod going on 8 years OK
    - AUG replaces year-to-year
  - testing shows decay > 100 eV, uncertainty in response below
- **no one yet has shown the ability to ‘correct’ for this**

*M. Bernert, RSI **85** 033503 (2014)*





While Slow, Bolometers Measure Greater Radiation Losses

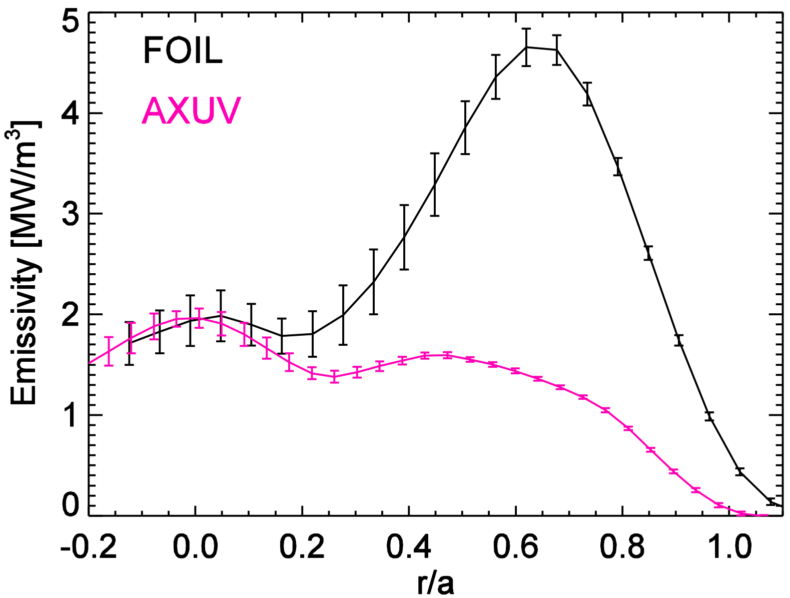


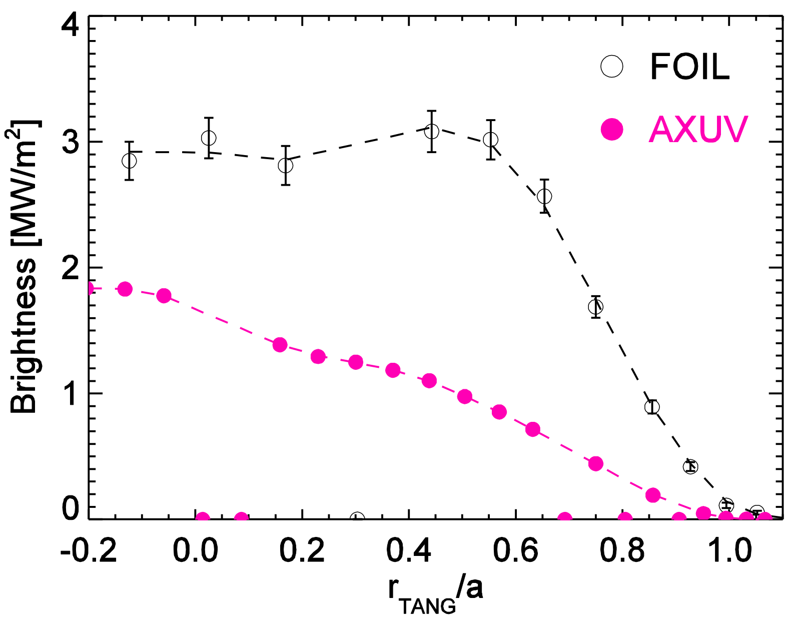
- examples from C-Mod tangential resistive bolometer and AXUV
  - strong n_z-puffing into Ohmic plasmas
- clear signal differences noticeable
  - observed to depend on r/a
- AXUV diodes proportional response while foil bolometers respond slowly
  - must be corrected for time constant

$$Br = Br_m - \tau * \frac{dBr_m}{dt}$$

  - Br_m shown, weak signals impact dBr_m/dt
  - τ ~ 100 ms, can evolve post-disruption
  - difficult to resolve fast transients
    - impurity injections
    - ELMs (done on AUG, JET)
    - sawteeth, NTMs
    - divertor oscillations (i.e. Potzel fluc.)

AXUV Diodes Are Insufficient for Power Balance





- example from C-Mod tangential resistive bolometer and AXUV
  - ICRF-heated inner-wall limited L-mode
  - Mo dominated $T_{e,0}$=3 keV $n_{e,0}$=1.8x10^{20} m^{-3}
- on-axis signals agree, higher T_e due to x-ray dominated emission from Mo
- integrate profiles over plasma volume assuming poloidal symmetry
  - AXUV: 0.8 MW radiated power
  - FOIL: 2.4 MW radiated power
- ratio of FOIL/AXUV varies 2→4
  - depends on T_e and impurity species
  - cannot explicitly correct as AXUV sensitivity is unknown – perhaps a neural network?
- **cannot accurately do power balance with AXUV-diode based diagnostics**

Desires for Radiation Measurements from NSTX-U Team

- Transport, RF & Macrostability
  - power balance, SOL & core localized radiation during RF
  - radiation within islands
  - radiation during disruption
- Scenarios
  - total radiated power (1 kHz), available between shots
  - radial profile of core radiation for high-Z/low-Z estimates
  - radiated power available for feedback control
- Pedestal, Boundary
  - pedestal resolved (1 cm resolution), with 1-2 kHz time resolution
  - power balance, divertor vs. core radiation, upper vs. lower div.
  - 2D (R,Z) reconstructions of radiated power density in divertor
  - 3D radiation distribution w/ non-axisymmetric fields

Reality of Radiation Measurements for NSTX-U

- Transport, RF & Macrostability
  - **power balance, SOL & core localized radiation during RF**
  - radiation within islands
  - radiation during disruption **(int. energy loss)**
- Scenarios
  - **total radiated power ~~(1 kHz)~~ (100 Hz) available between shots**
  - **radial profile of core radiation for high-Z/low-Z estimates**
  - **radiated power available for feedback control** (likely both)
- Pedestal, Boundary
  - pedestal resolved (1 cm resolution), with 1-2 kHz time resolution
  - **power balance, divertor vs. core radiation, upper vs. lower div.**
  - **2D (R,Z) reconstructions of radiated power density in divertor***
  - 3D radiation distribution w/ non-axisymmetric fields*

AXUV Diodes
Resistive Bolometers

***exploit IR-imaging bolometers?**

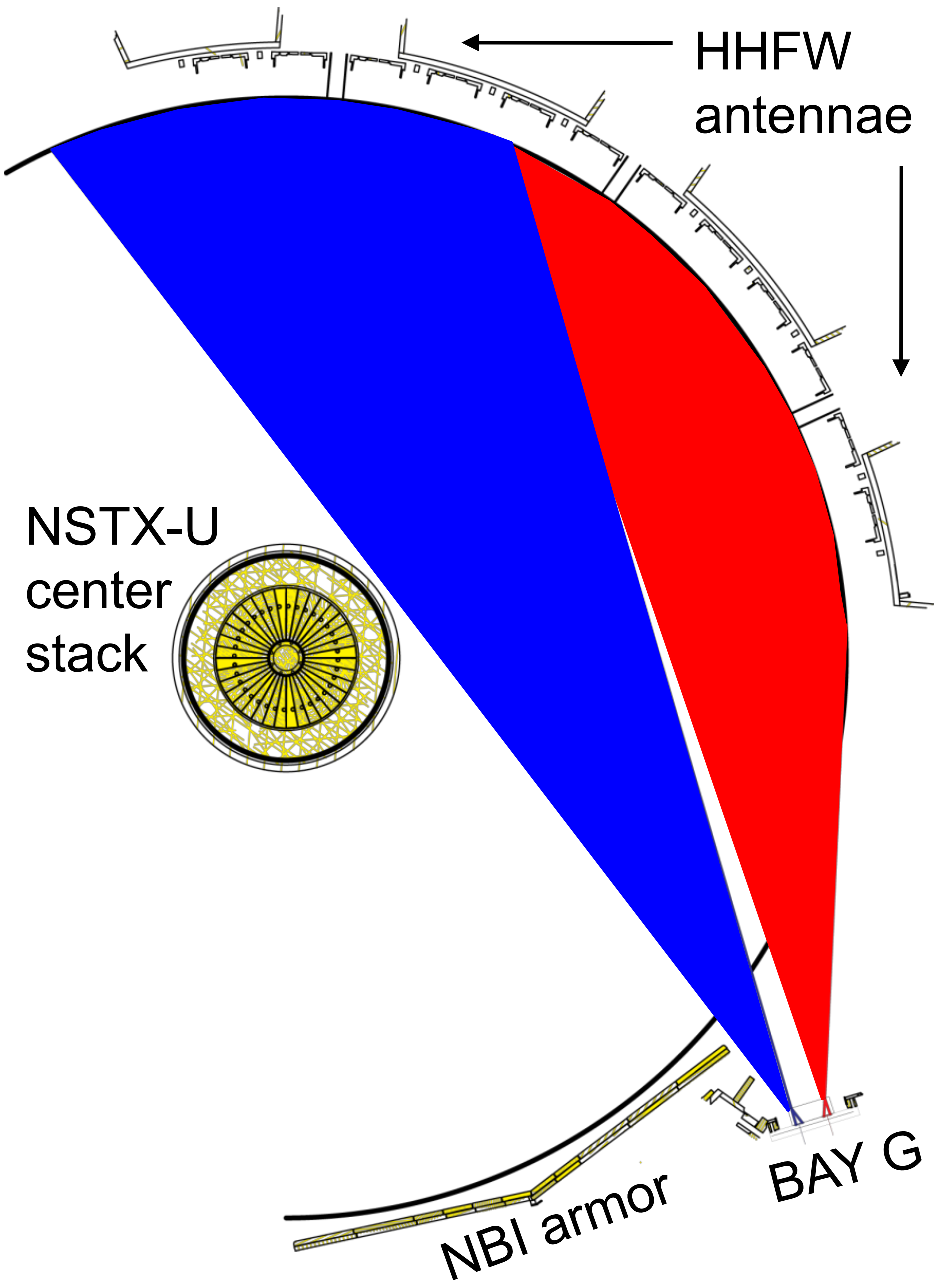
Timetable for Radiation Measurements for NSTX-U

- Transport, RF & Macrostability
  - **power balance, SOL & core localized radiation during RF**
  - radiation within islands
  - radiation during disruption **(int. energy loss)**

FY17
FY18+

- Scenarios
  - **total radiated power ~~(1 kHz)~~ (100 Hz) available between shots**
  - **radial profile of core radiation for high-Z/low-Z estimates**
  - **radiated power available for feedback control**
- Pedestal, Boundary
  - pedestal resolved (1 cm resolution), with 1-2 kHz time resolution
  - **power balance, divertor vs. core radiation, upper vs. lower div.**
  - **2D (R,Z) reconstructions of radiated power density in divertor**
  - 3D radiation distribution w/ non-axisymmetric fields

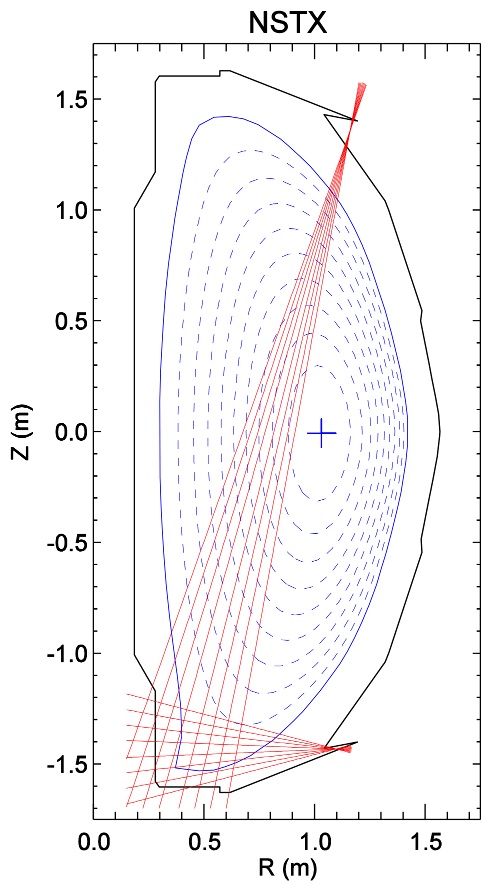
Capabilities for FY15/16 NSTX-U Operations

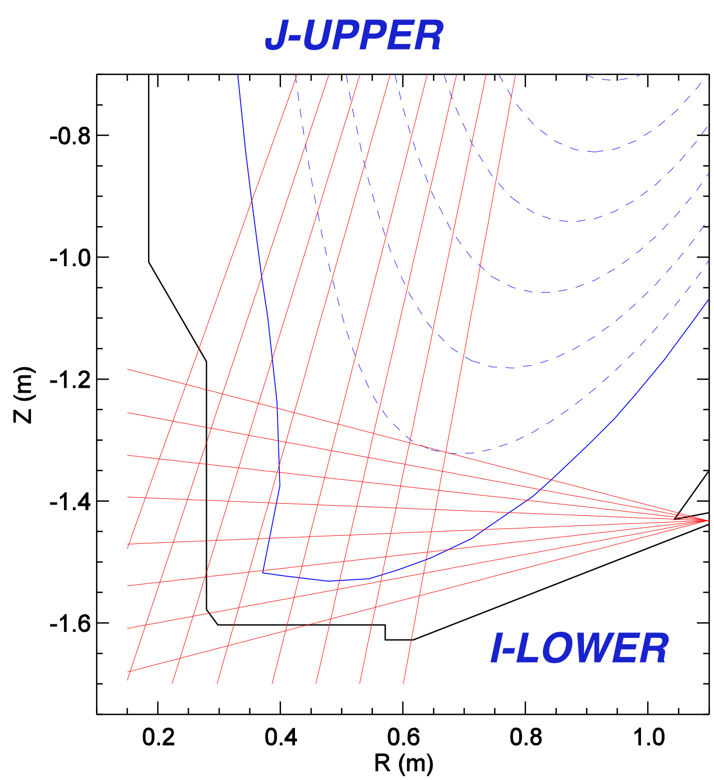


- midplane AXUV (Bay-G)
  - x2 20-channel AXUV diode arrays view tangentially on midplane
  - resolve in/out asymmetry
  - compute estimate of core radiated power by volume integrating
- edge AXUV (Bay-G)
  - 20-channel LFS edge
  - tangential view just below midplane
  - unfiltered portion of ME-SXR
- divertor AXUV (Bay-G)
  - the Ly_α camera w/o Ly_α filter
  - 20-channel poloidal view
  - spans divertor region and LFS edge

Existing NSTX Resistive Bolometer System

- x3 pinhole cameras at J-UPPER (8-ch), I-LOWER (8-ch) and J-MIDPLANE (4-ch, not shown) highlighting the divertor
- never utilized, prior iterations had far fewer channels installed
  - no hardware was reinstalled for NSTX-U





J-UPPER camera

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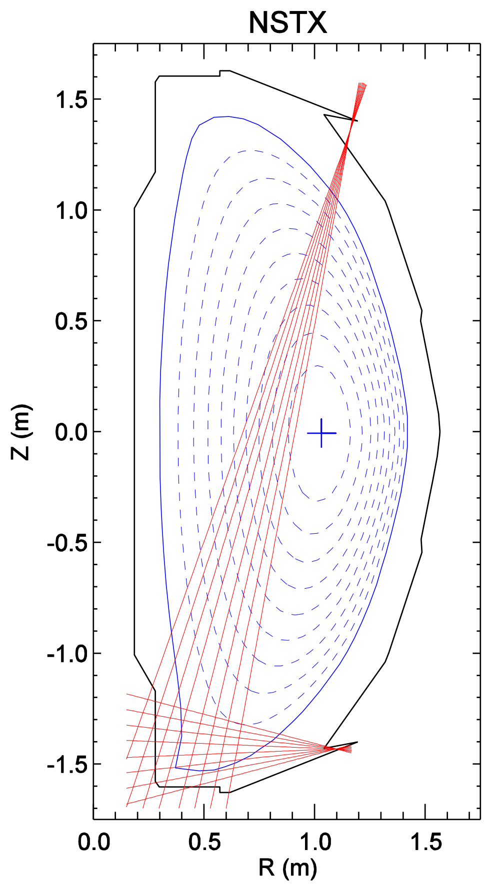
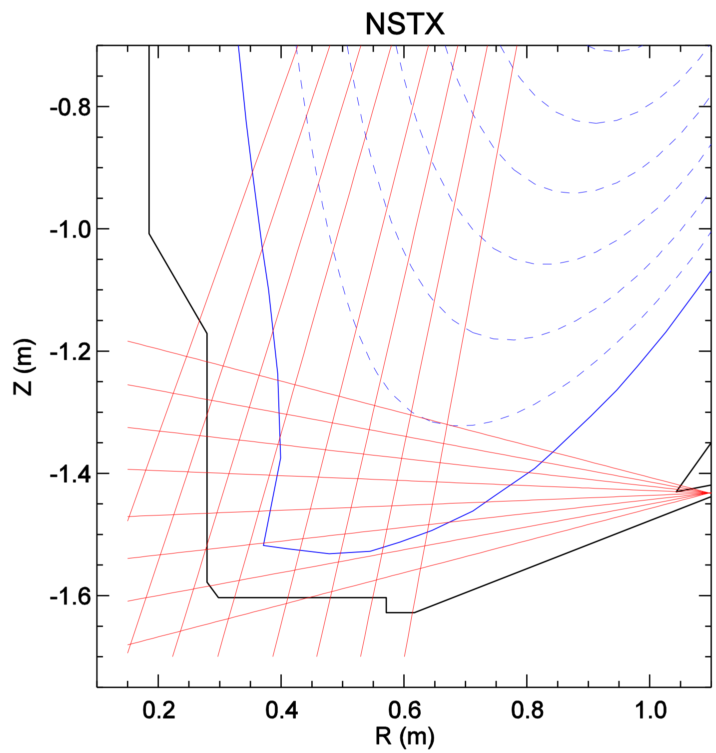
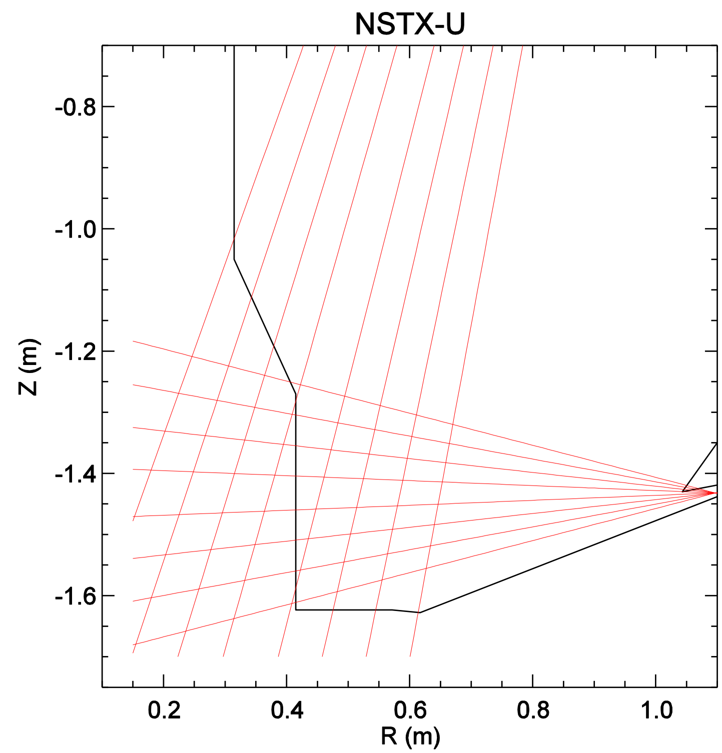


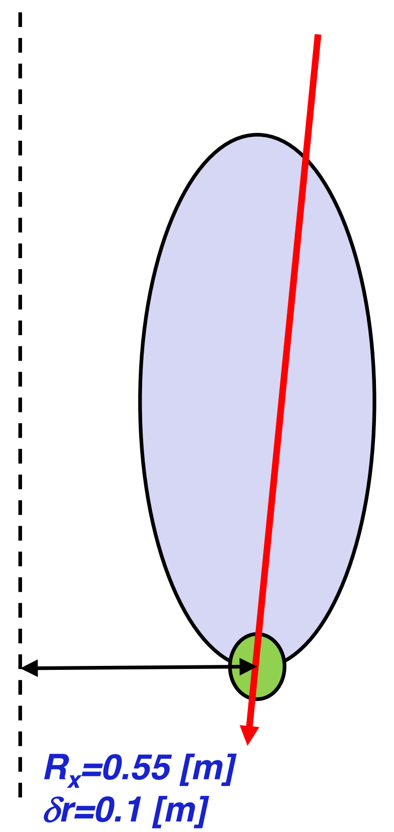
modification of viewing geometry needed

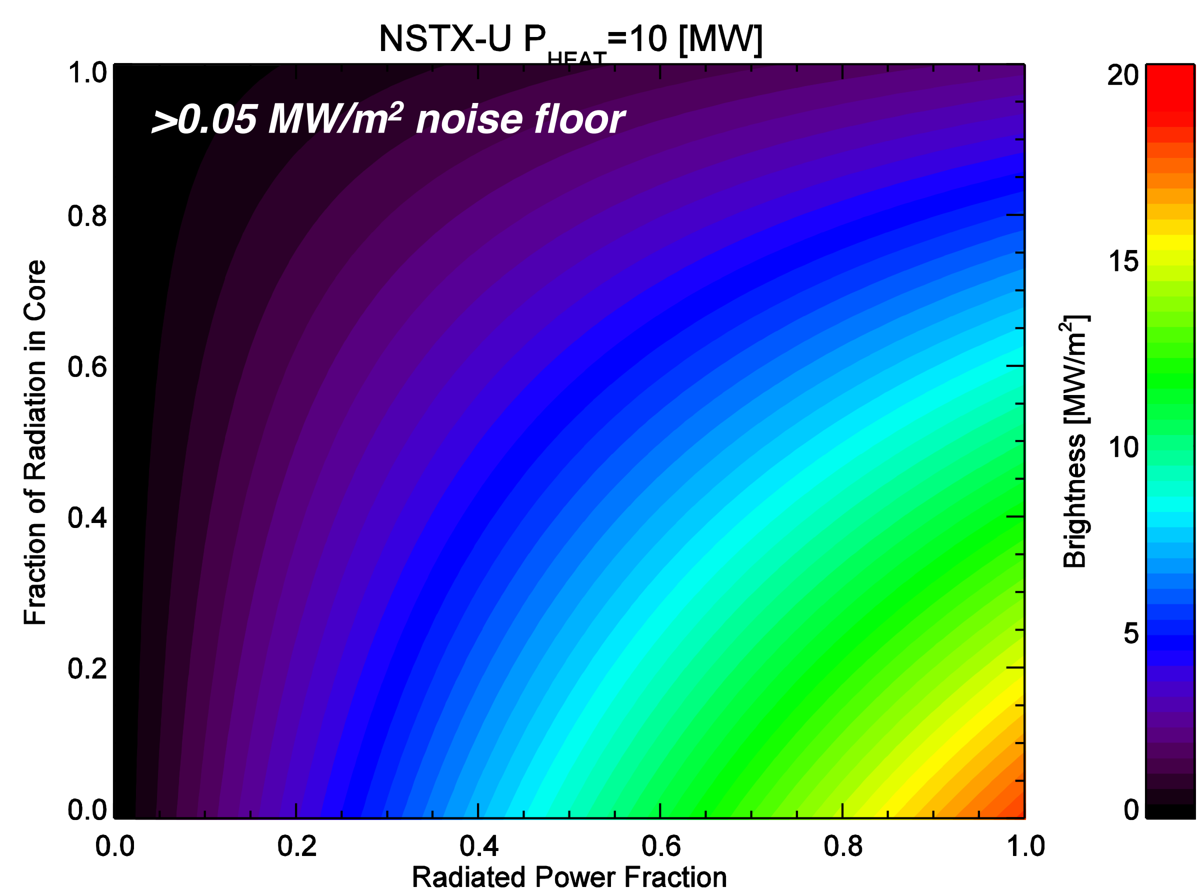




Estimates Suggest Sufficient Radiation in Many Scenarios

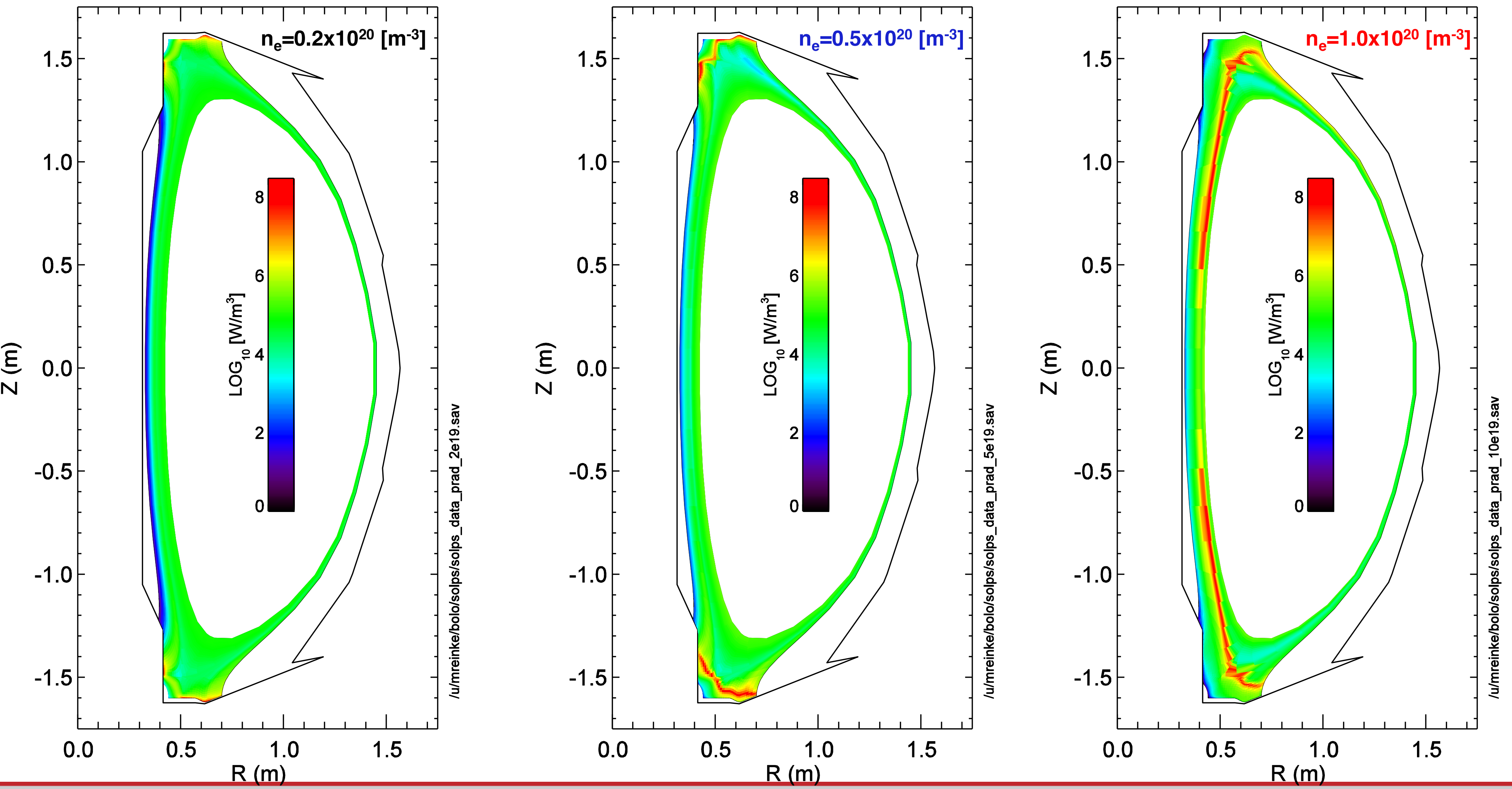
- use radiated power fractions to esimate signal levels
  - core emissivity = $f_{RAD}*f_{CORE}*P_{HEAT}/Vol_{CORE}$
  - ‘divertor’ emissivity = $f_{RAD}*(1-f_{CORE})*P_{HEAT}/Vol_{DIV}$
- line integrate through both volumes



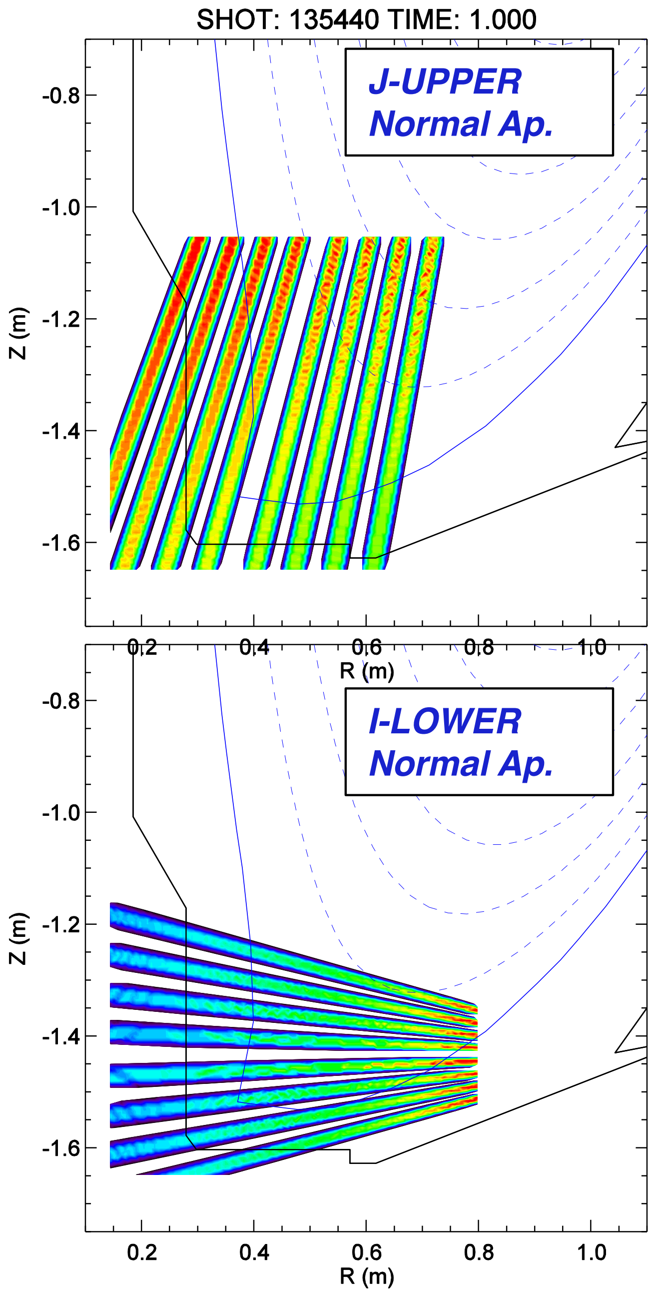


Further Scoping Using SOLPS Simulations (J. Lore)

- density scan at 10 MW to access different divertor regimes
- results show movement of narrow radiation features



Spatial Resolution Sufficient, Possibly Too Constrained



- ported tools from C-Mod to assist in diagnostic design (GENPOS)
  - assumes axisymmetry
  - grid detector/aperture and traces hyperbolic paths through tokamak
  - plot ‘voxel’ weightings on (R,Z) plane (contour plots – left)
- old design uses a circular pinhole which doesn’t exploit axisymmetry to increase signal

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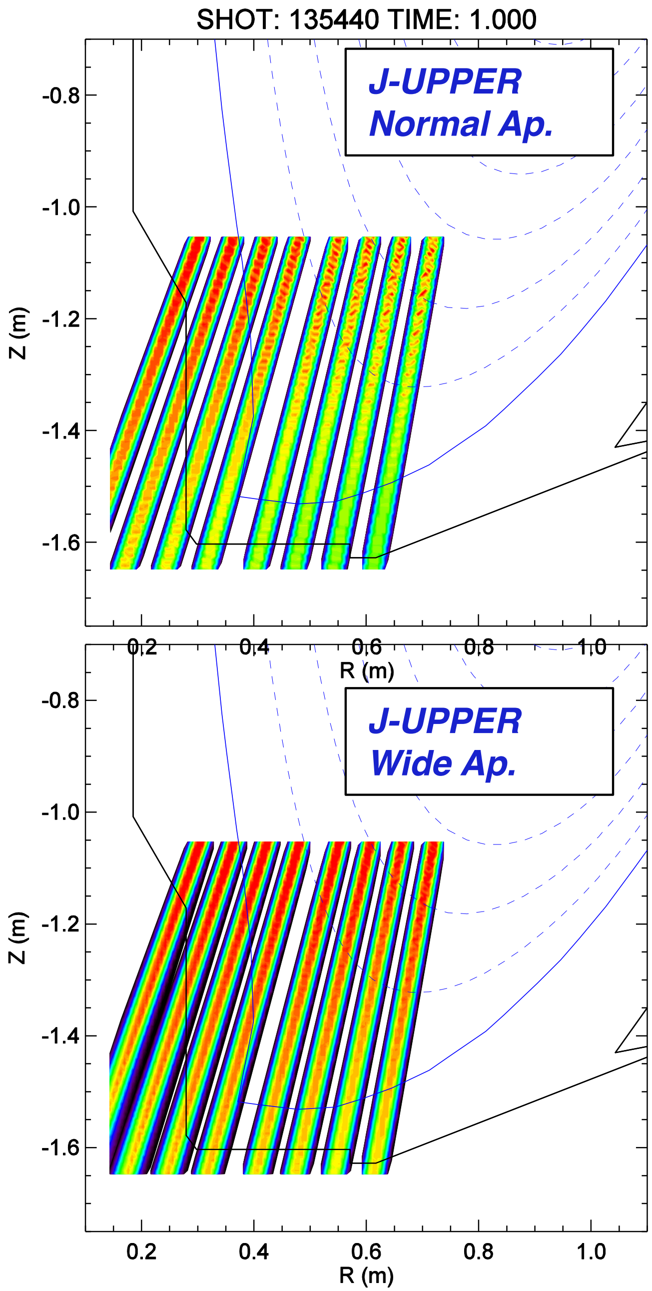

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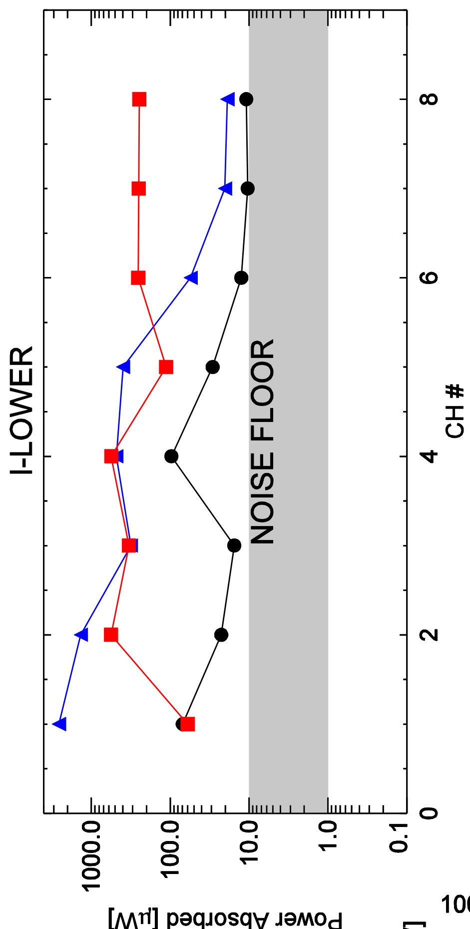
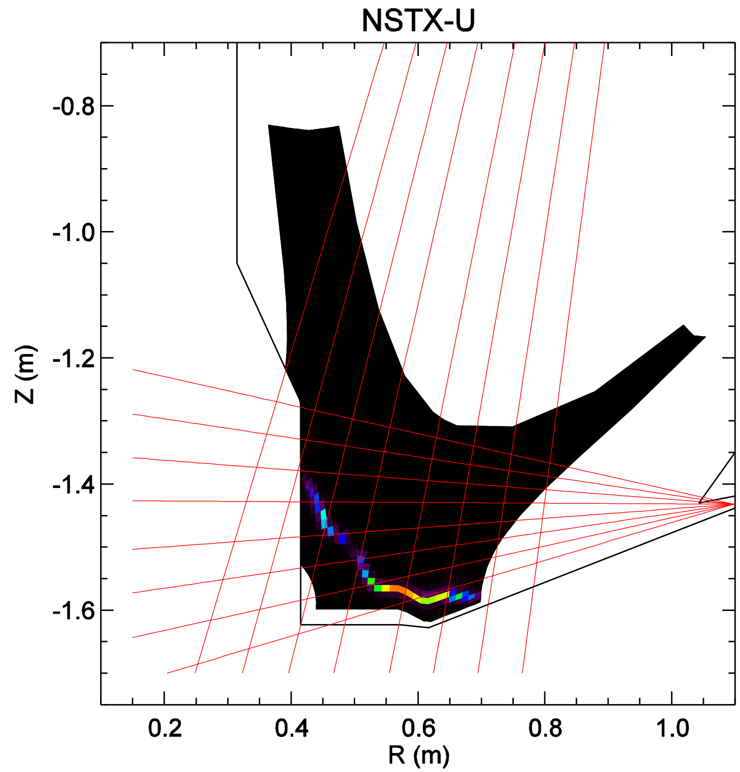
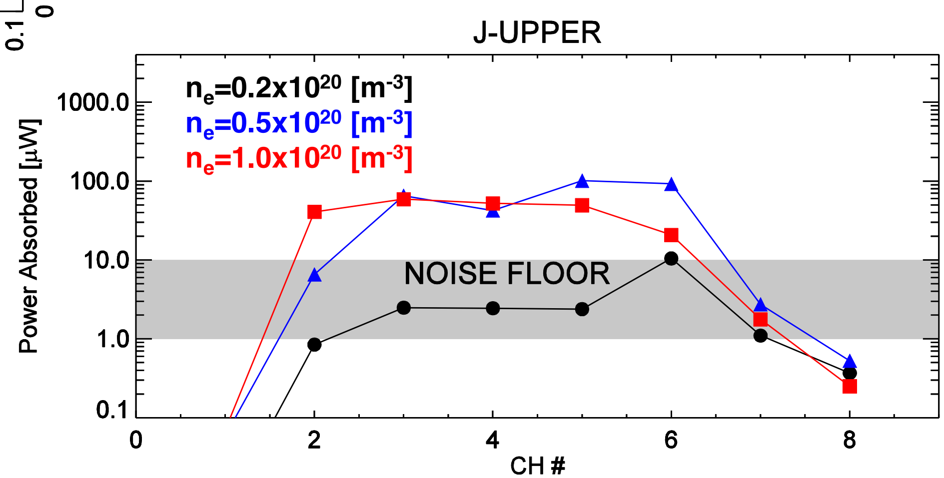
  - assumes axisymmetry
  - grid detector/aperture and traces hyperbolic paths through tokamak
  - plot ‘voxel’ weightings on (R,Z) plane (contour plots – left)
- old design uses a circular pinhole which doesn’t exploit axisymmetry to increase signal
  - increase signal by x5 by increasing toroidal extent of aperture
  - flexibility in signal/resolution optimization

Radiation Structures Observable with Sufficient Signal

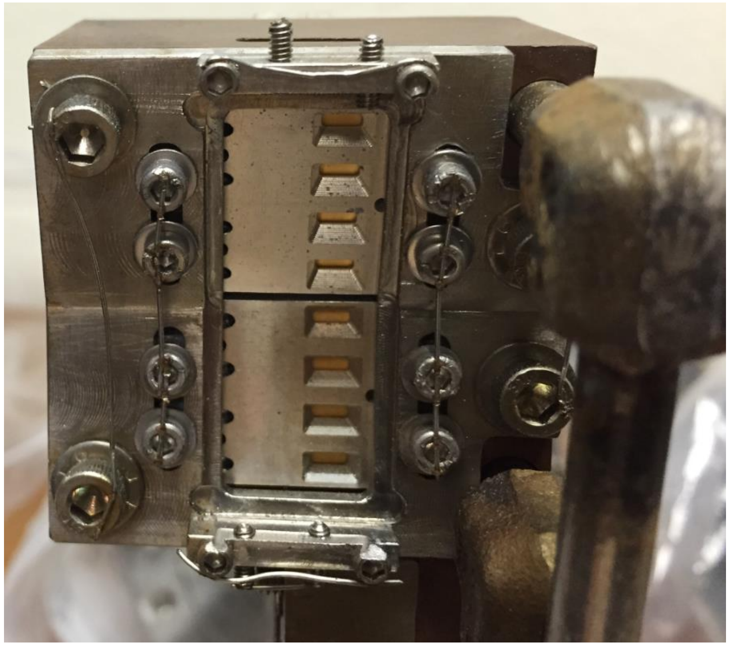




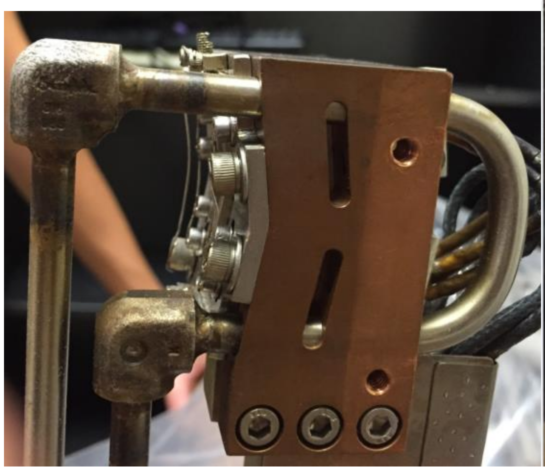


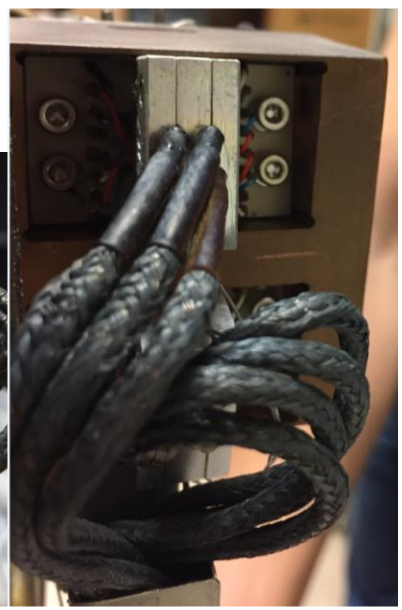
- 'tweaked' views to be NSTX-U relevant
- computed signals based on finite ap.
  - f_{RAD} < 10%
  - f_{RAD} ~ 30% (shown)
  - f_{RAD} ~ 75%
- at low f_{RAD}, signals approach noise floor
  - 'hand-off' to the IR for power balance
- **w/ small changes, lower divertor system feasible for FY17 operations**

Need to Improve Thermal Management During Bake



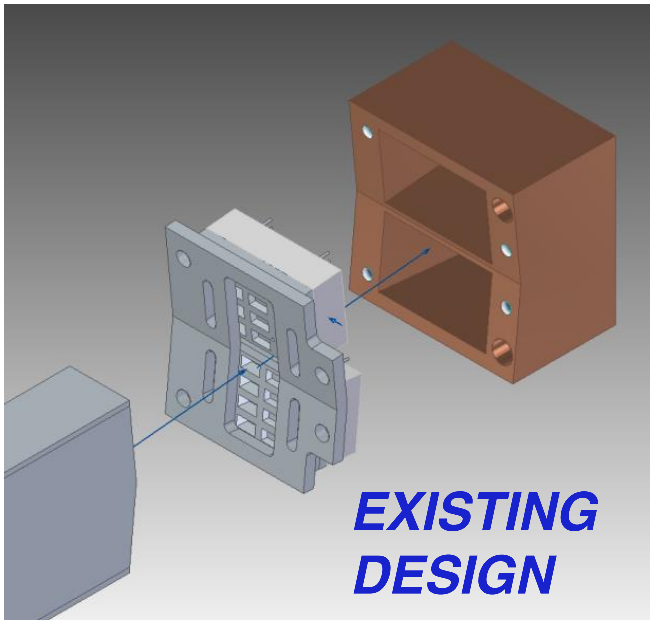
I-LOWER camera without 'snout' that has aperture

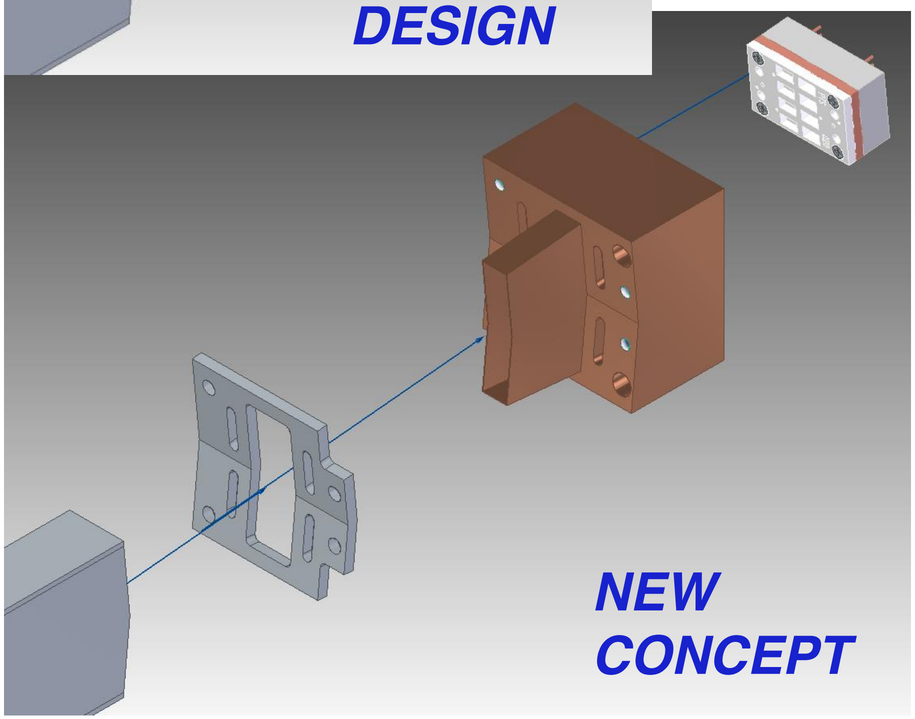




- previous failure of the resistive bolometers thought to be tied to bake
  - survive C-Mod, AUG ~ 150 °C, no cooling
  - survive DIII-D 300 °C bake (different res. bolometer) w/ active cooling and *interlock!*
- cooling design is very poor if goal is thermal management of gold foil
  - bolometer housing is not physically attached to copper cooling sink
    - attached to stainless shield plate
    - must radiatively cool w/ heat sink
  - gold foil element is designed to have poor conduction to housing which is what makes it a good bolometer
    - it sees wide angle view of 'snout' which is up at bake temperature

Concepts to Improve Bolometer Survivability

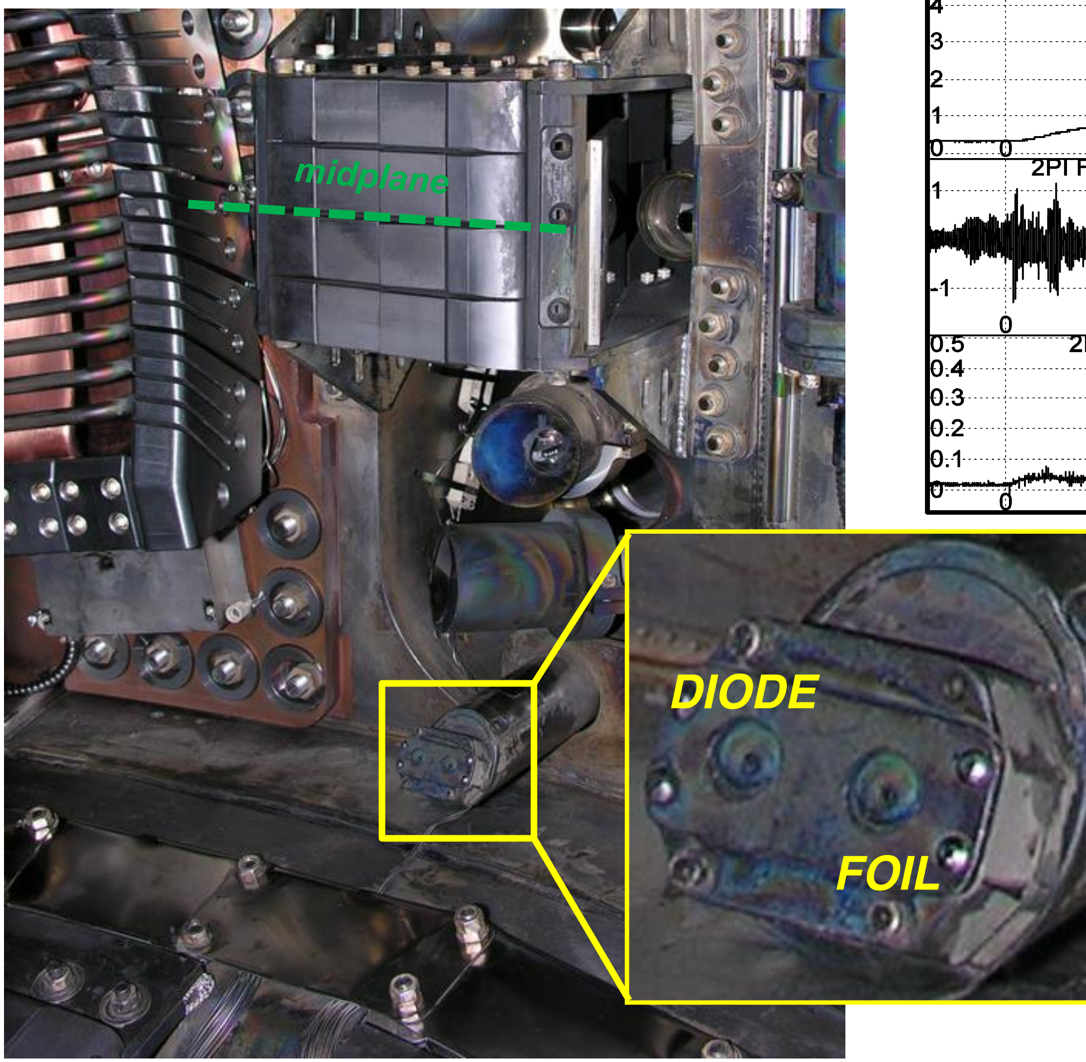


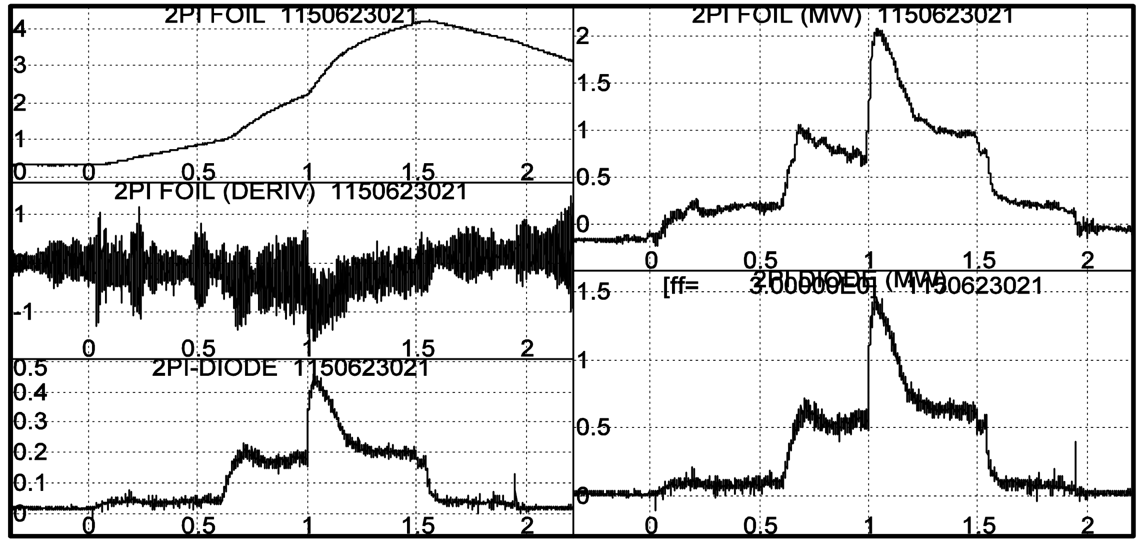


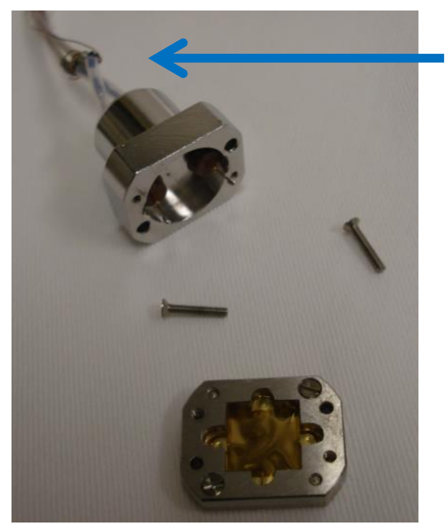
- use the bolometer itself to monitor the temperature, no thermocouple needed
  - calibrate the ‘time constant’ the pinhole camera to external heating
  - bolometer → comparator circuit → EPICS, monitor time evolution, shut down the bake
- improve mechanical design to better handle heat bake
  - double cooling loops?
  - attach bolo housing to heat sink
  - collimate FOV of foil element from structures at bake temp
  - ***route heat around critical temperature element rather than through it!***

Operations Support – Global ‘2π’ Bolometer

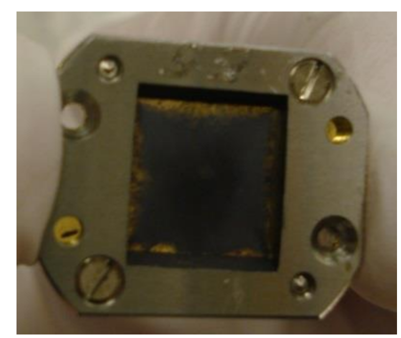
- sacrifice localization and for a robust ‘global’ radiation from a single channel wide-angle view (C-Mod: diode & foil)





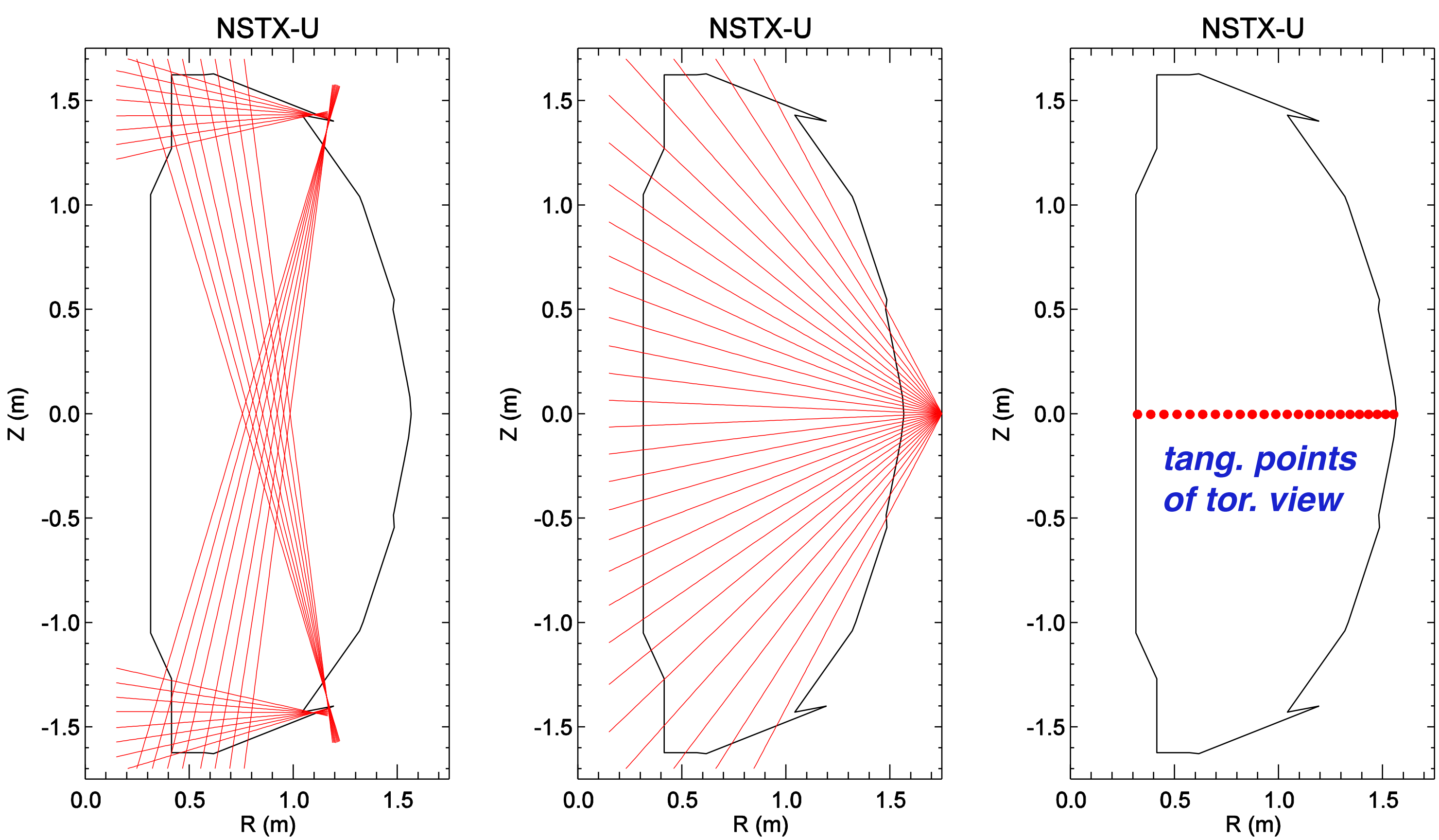


two wire output to resistance comp. circuit w/ derivative



If Wishing Made It So…..

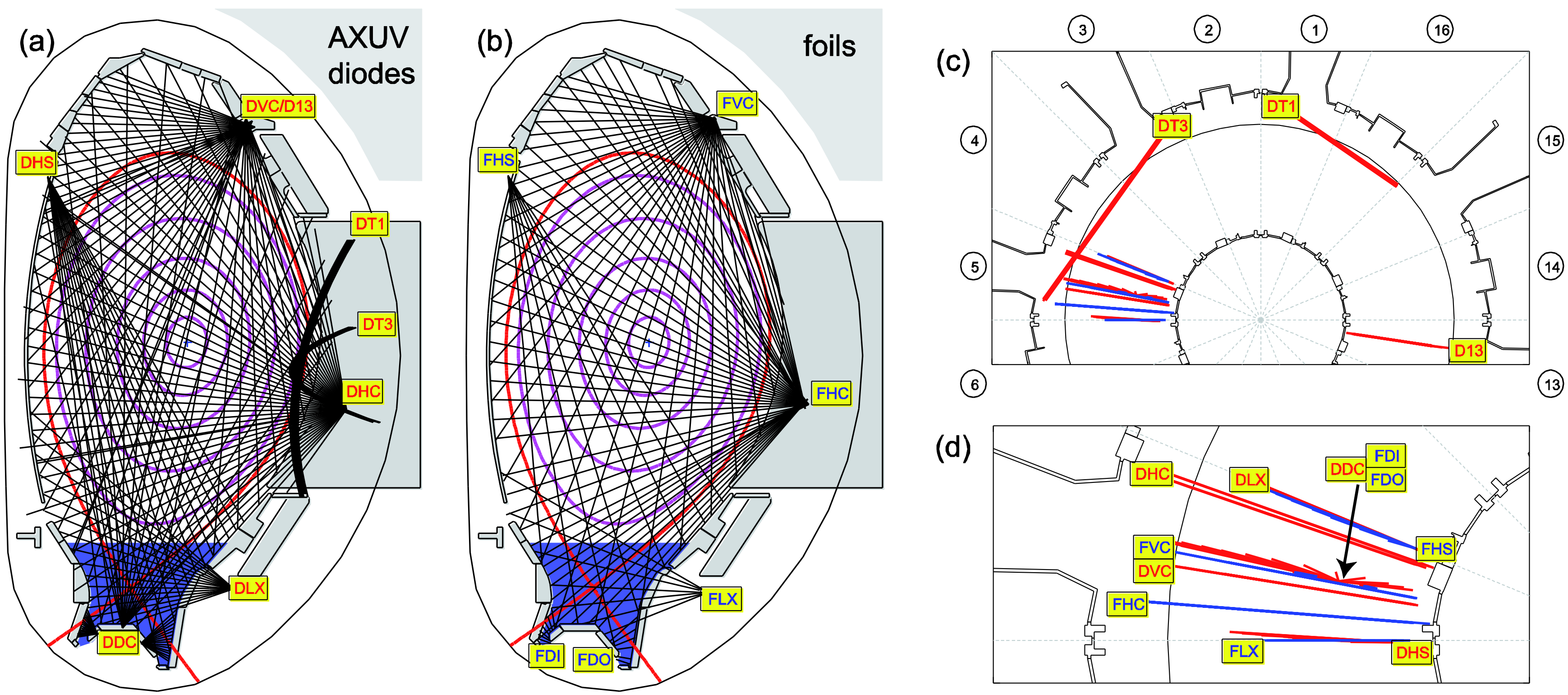
- scoping for 84-channel to deliver on objectives discussed earlier
  - power balance, core vs. divertor radiation, intershot analysis
- large demand on resources, but looking to deliver measurement which is usually established *early* in the life cycle of most tokamaks



look to how IR-based bolometers might assist, but technology is more risky than resistive bolometers

If Wishing Made It So…..

- scoping for 84-channel to deliver on objectives discussed earlier
  - power balance, core vs. divertor radiation, intershot analysis
- large demand on resources, but looking to deliver measurement which is usually established *early* in the life cycle of most tokamaks
  - moves us closer to system like ASDEX-Upgrade which has sufficient AXUV (256-ch) and resistive bolometers (112-ch) to study 2D & 3D structures



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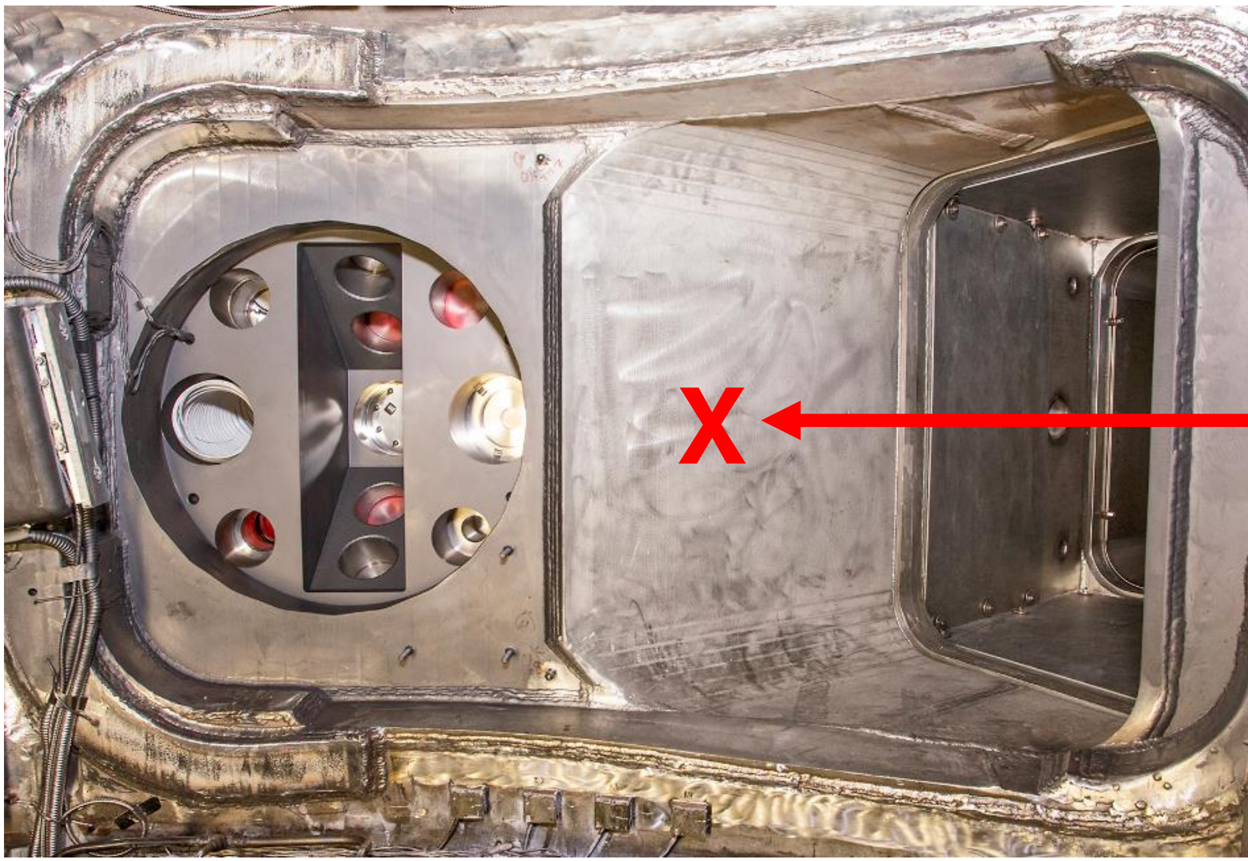
Core Radiation From Tangential View?

- tangential midplane view optimal to measure core radiation
  - easy to interpret, overcomes largest pol. asymmetry (IN/OUT)
- suggest exploring view from NBI-2 beam duct
  - compact pinhole cameras can utilize space between VV & coils



make minimal hole for FOV, set aperture back from duct wall

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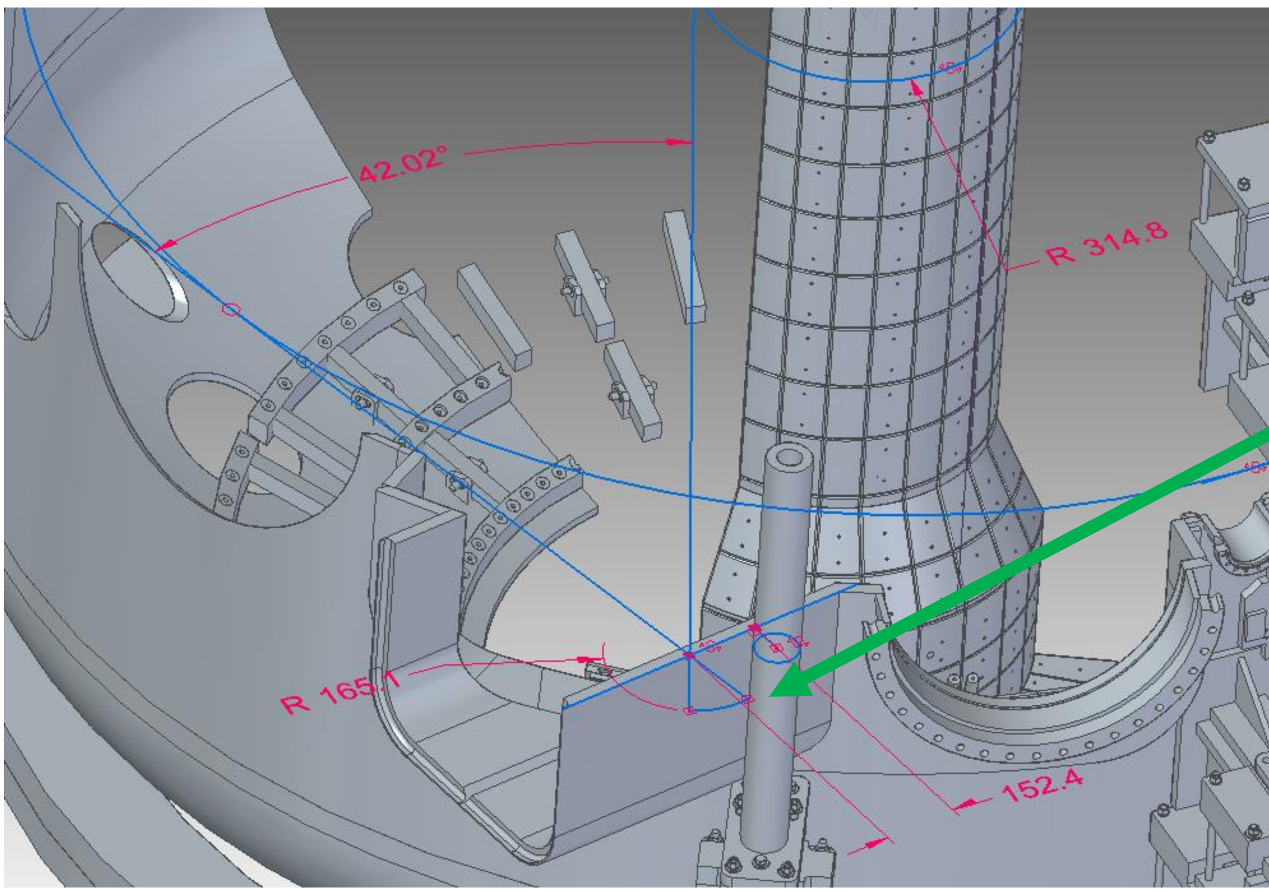
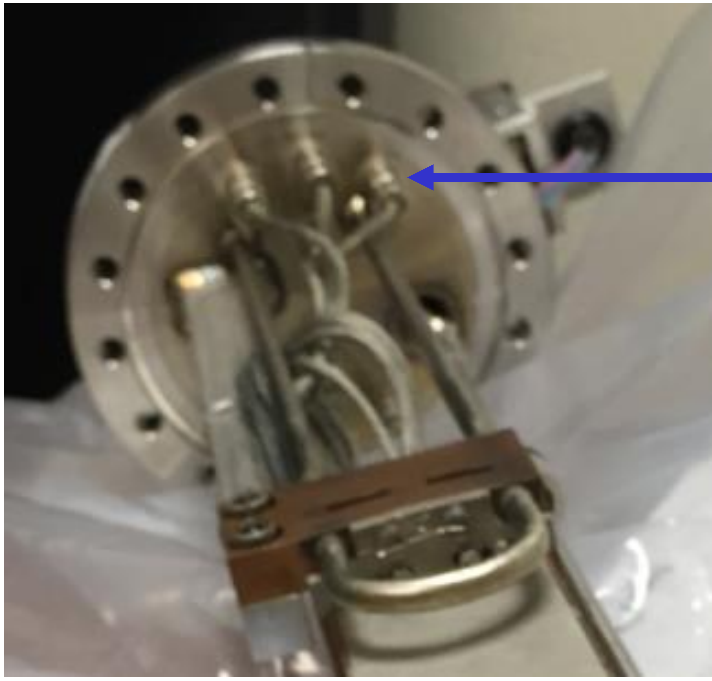
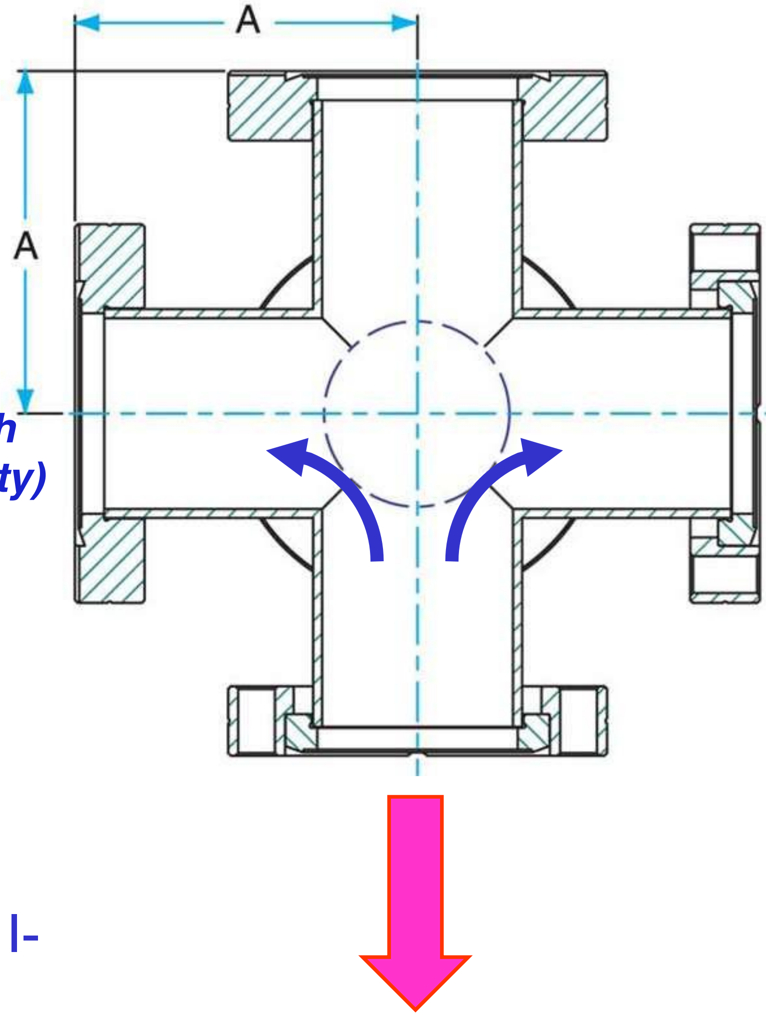


a 32-channel system could view from LFS to HFS and doesn't NOT fit

Try to Increase Channel Count per Flange

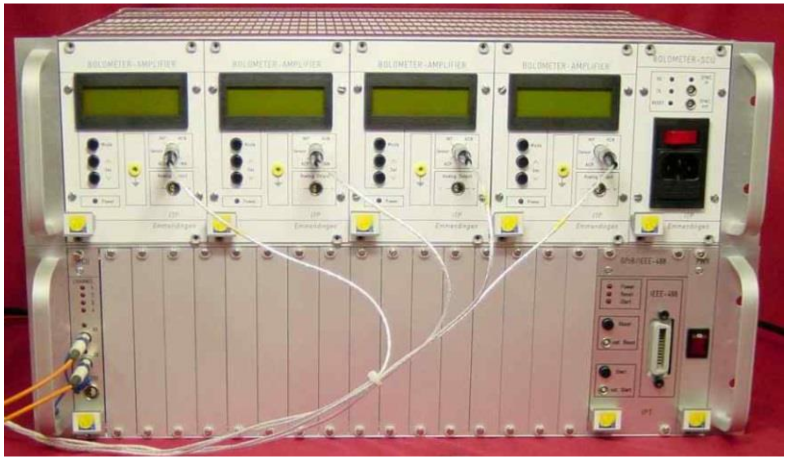


present J-UPPER camera



- present 8-ch per 6-3/4” flange
- use 2D or 3D cross to expand
  - easily get > 32 channels
  - issue with port-to-floor distance on I-LOWER

Try to Reduce Analyzer Cost/Channel



4-channel analyzer/amplifier from IPT-Albrecht

Drawing 2: BOLO8BLF

Drawing 3: 6x BOLO8BLF in ACQ2006 - 48 Channel System

48-channel analyzer from D-tAcq (prototype)

- present electronics are expensive take up significant space
  - **12 k$ per 4-channel unit**
  - GPIB-based configuration and control
- new FPGA-based system under development and demonstration
  - motivated by MAST-U cost needs
  - G. Naylor (CCFE), J. Lovell & R. Sharples (Durham Univ.)
    - data from Univ. of York bolo test-stand
  - by D-tAcq so it plays well with MDSPlus
  - **15 k$ for 32-channel unit**
- **D-tAcq system not fully costed and risk-assessed, but likely will be a means of major cost reduction**

Summary

- NSTX-U stands out amongst large fusion facilities by its lack of resistive bolometers
- resistive bolometers are necessary for power balance and cannot be replaced by AXUV diodes
  - AXUV diodes complement resistive bolometers
- existing designs for resistive bolometers viewing the lower divertor should be adaptable for FY17 ops
  - need to adjust lines of sight, throughput & thermal management
- development needed beyond FY17 to deliver measurements necessary for power balance & more
  - several risk (IR, resistive) and cost (port space, $$) mitigation strategies need to be considered